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# Towards a Compelling Physics Case for a Future eRHIC

Marco Stratmann

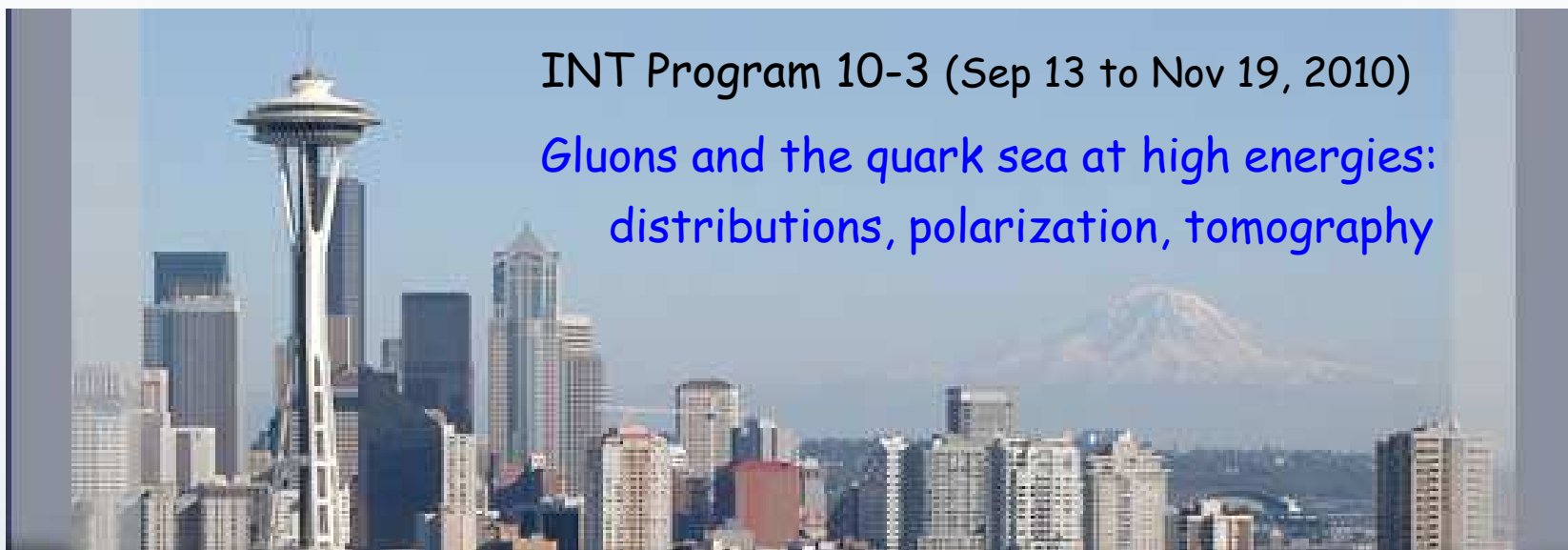
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Office of  
**SCIENCE**  
U.S. Department of Energy





INT Program 10-3 (Sep 13 to Nov 19, 2010)

Gluons and the quark sea at high energies:  
distributions, polarization, tomography

**organizers:** D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang

**strong BNL  
involvement**

**convenors:** D. Hasch, M.S., F. Yuan *spin & PDFs*

M. Burkardt, V. Guzey, F. Sabatie *imaging*

A. Accardi, M. Lamont, C. Marquet *eA*

K. Kumar, Y. Li, W. Marciano *beyond SM*

**main goal:** sharpen the physics case for an EIC for next NSAC long range plan

- identify outstanding open questions in hadronic physics still relevant in 10+ years
- devise key “golden” measurements in ep and eA to address these questions
- quantify experimental needs & requirements and study feasibility

**very successful, well attended program; most goals accomplished**

detailed 500+ pages write-up is in its finishing stages - to appear on the arXiv soon

joint BNL/INT/JLab  
publication

Proceedings of the joint BNL/INT/JLab program

Gluons and the quark sea  
distributions, polarization

Institute for Nuclear Theory, University of  
September 13 to November 13, 2009

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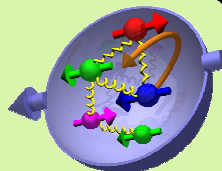
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but no time to sit & relax

- studies for identified **"golden measurements"**  
need to be substantiated & feasibility demonstrated
- input for community wide white paper (draft by end of 2011)

# most compelling physics questions

## spin physics



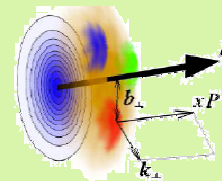
what is the polarization of gluons at small  $x$  where they are most abundant



what is the flavor decomposition of the polarized sea depending on  $x$

**determine quark and gluon contributions to the proton spin at last**

## imaging



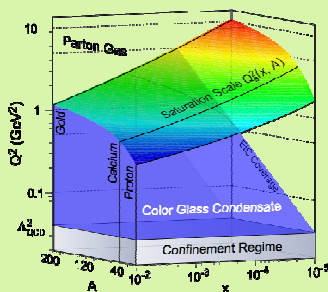
what is the spatial distribution of quarks and gluons in nucleons/nuclei



understand deep aspects of gauge theories revealed by  $k_T$  dep. distr'n

**possible window to orbital angular momentum**

## physics of strong color fields



understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation  
how do hard probes in eA interact with the medium



**quantitatively probe the universality of strong color fields in AA, pA, and eA**

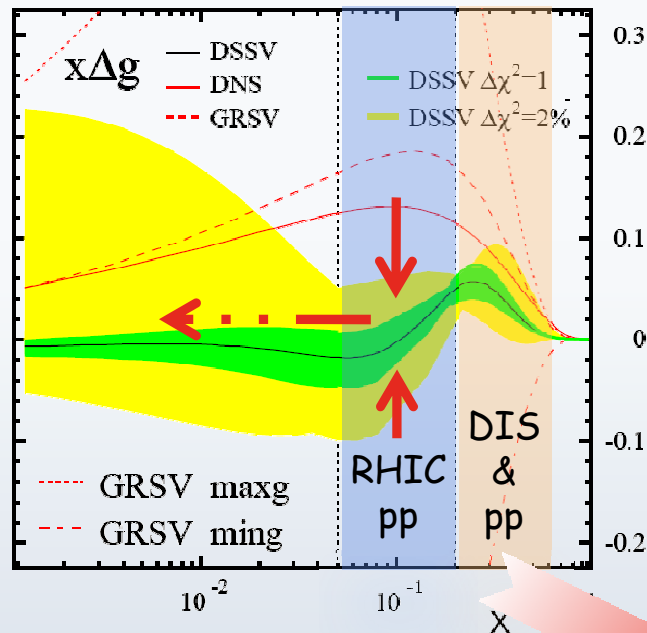


# SELECTED "GOLDEN" MEASUREMENTS

# the quest for the spin of the proton: $\Delta g$

current status:

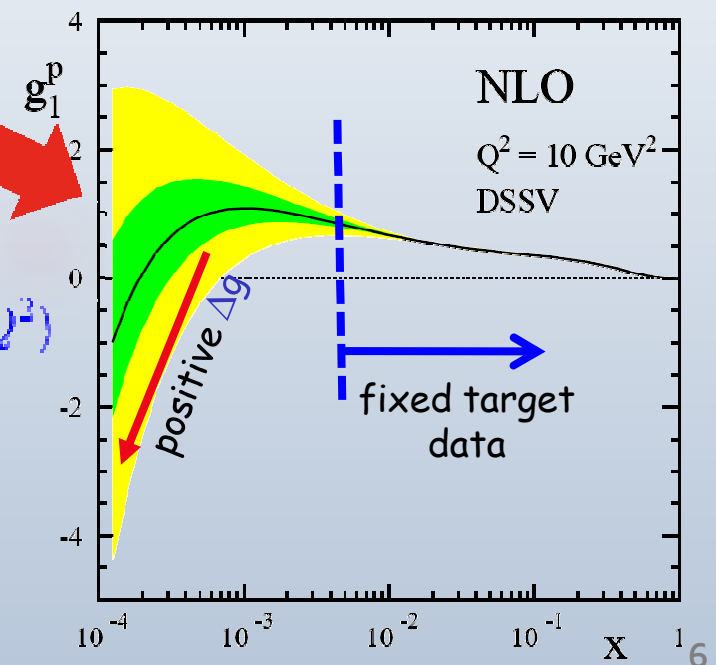
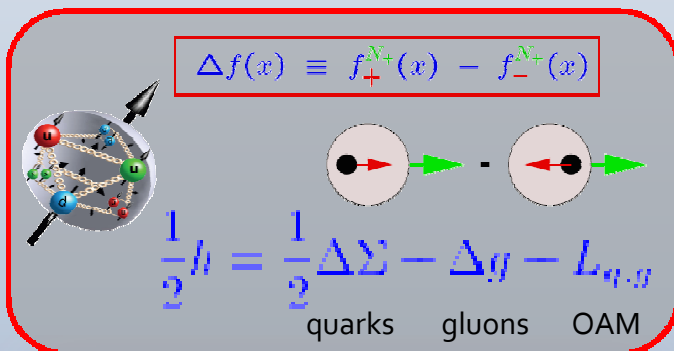
DSSV global fit  
de Florian, Sassot,  
MS, Vogelsang



- low  $x$  behavior unconstrained  
significant polarization still possible
- no reliable error estimate for 1<sup>st</sup> moment  $\int_0^1 dx \Delta g(x, Q^2)$   
(enters spin sum rule)
- RHIC will continue to improve our knowledge at medium  $x$

best probe for small  $x$  gluons  
pQCD scaling violations

$$\frac{dg_1(x, Q^2)}{d \ln Q^2} \propto -\Delta g(x, Q^2)$$



# what can be achieved for $\Delta g$ at eRHIC

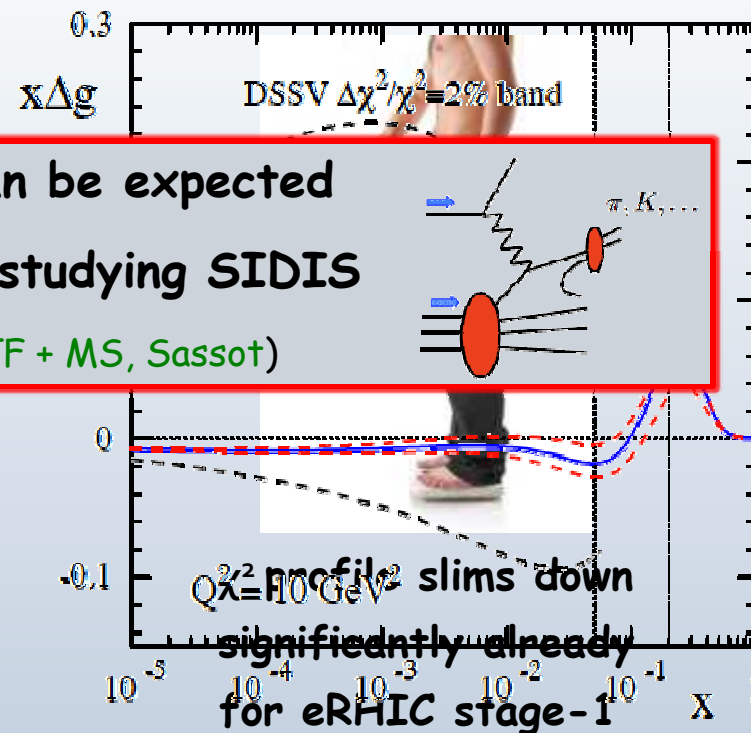
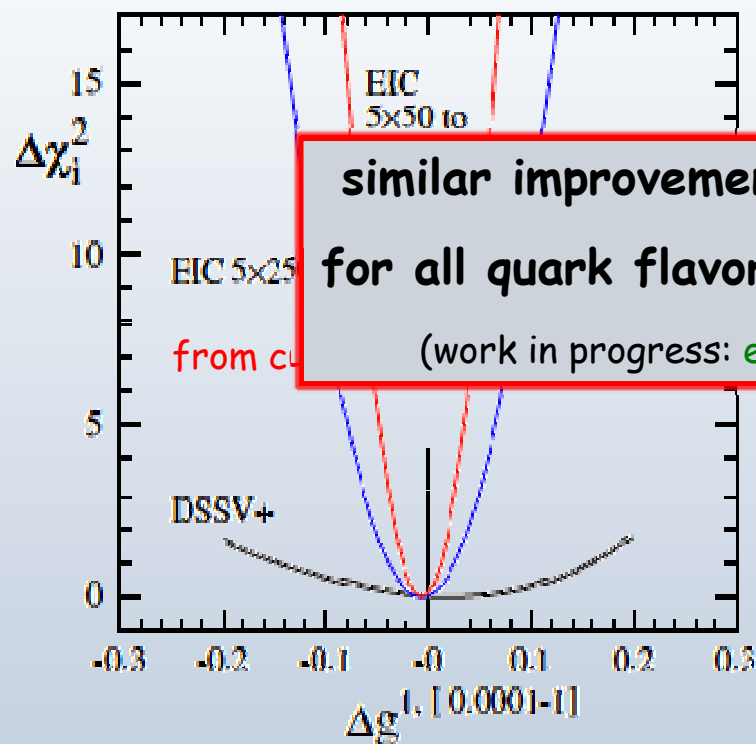
how effective are scaling violations ?

Sassot, MS

quantitative studies based on simulated data for stage-1:  $5 \times (50, 100, 250, 325)$  GeV

$\chi^2$  profile for  $\int_{10^{-4}}^1 \Delta g(x, Q^2) dx$

uncertainties on the x-shape of  $\Delta g(x, Q^2)$



similar improvements can be expected  
for all quark flavors by studying SIDIS  
(work in progress: eRHIC TF + MS, Sassot)

expect to determine  $\int_0^1 dx \Delta g(x, Q^2)$  at about 10% level (or better - more studies needed)

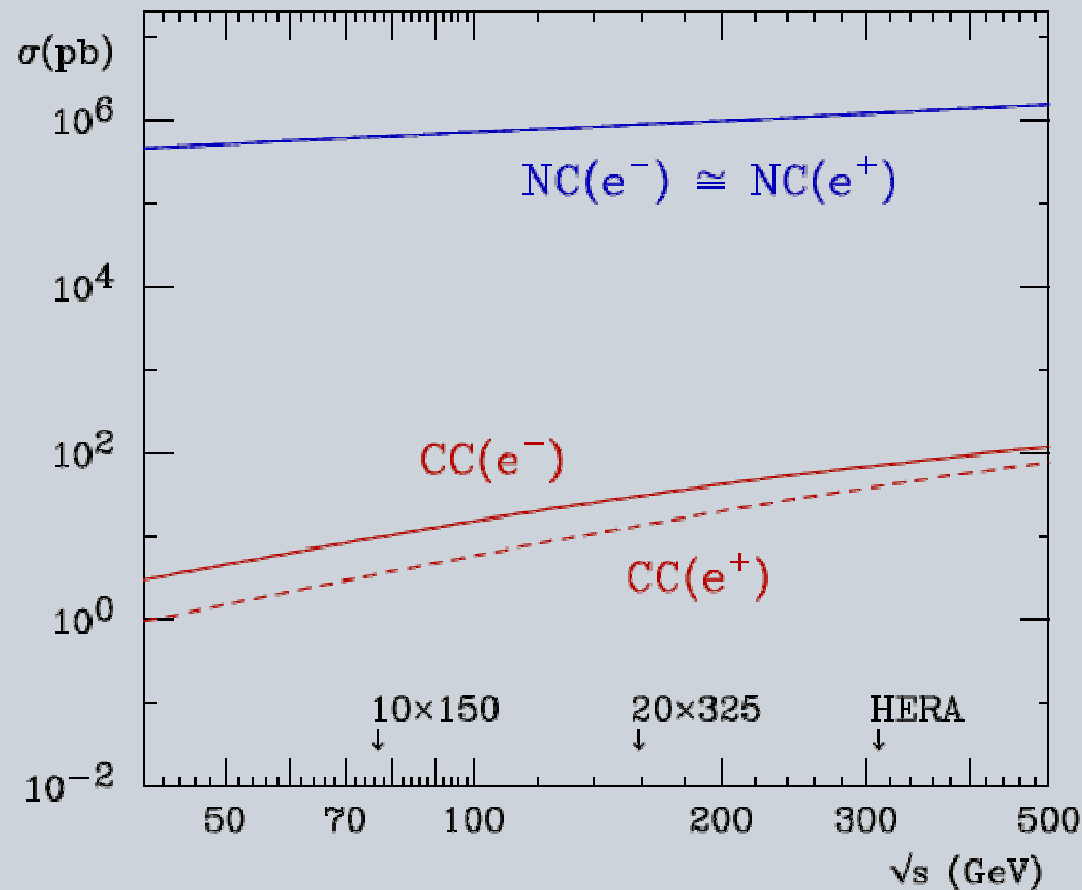
kinematic reach down to  $x = 10^{-4}$  essential to determine integral

# large $Q^2$ : novel electroweak probes for $\Delta q$ 's

Taneja, Vogelsang

key for e-w measurements at eRHIC:

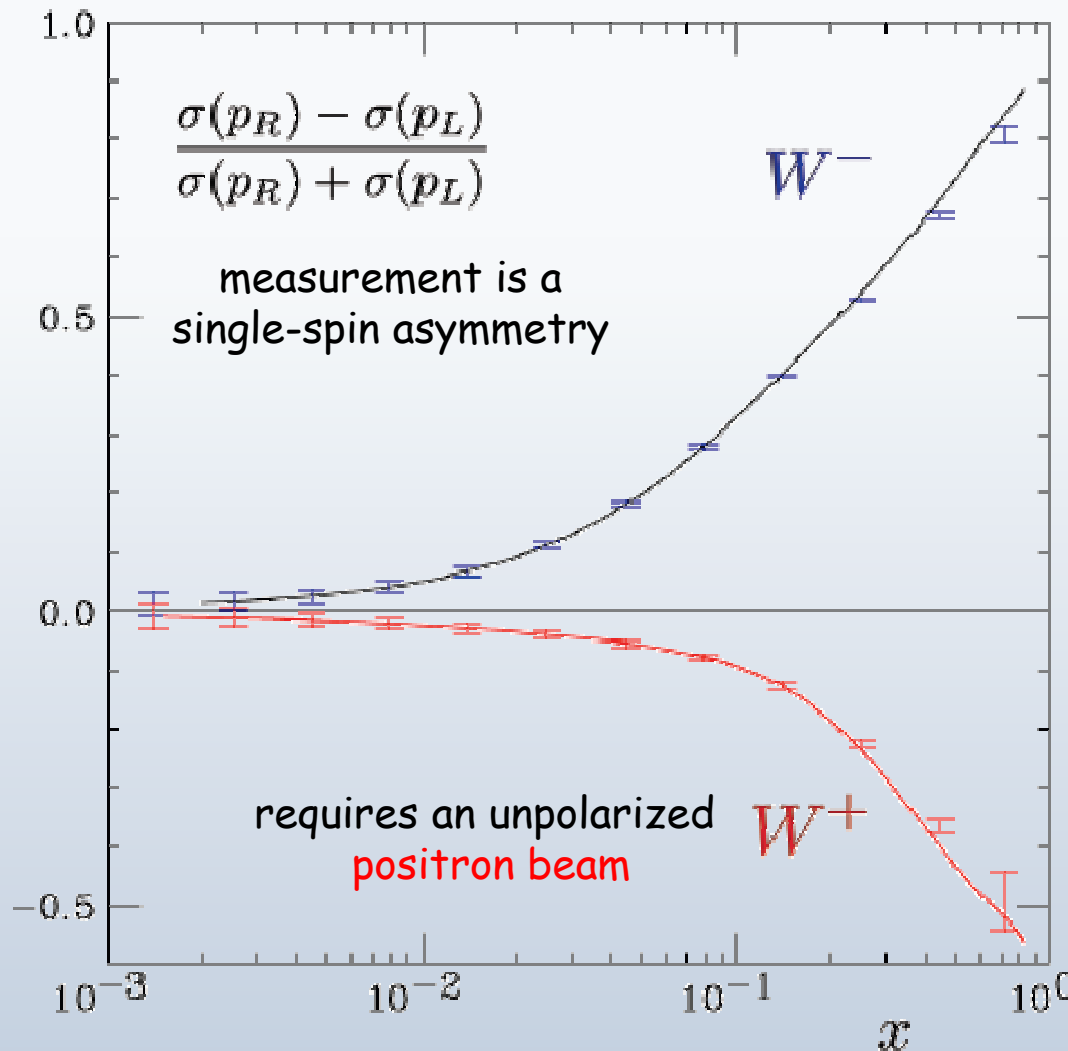
drop in cross section more than compensated by luminosity increase



unexplored so far - unique opportunity for the EIC



# most promising: charged current DIS



20 250 GeV

DIS cuts

10 fb<sup>-1</sup>

need to be able to reconstruct  $x, Q^2$  from hadronic final-state

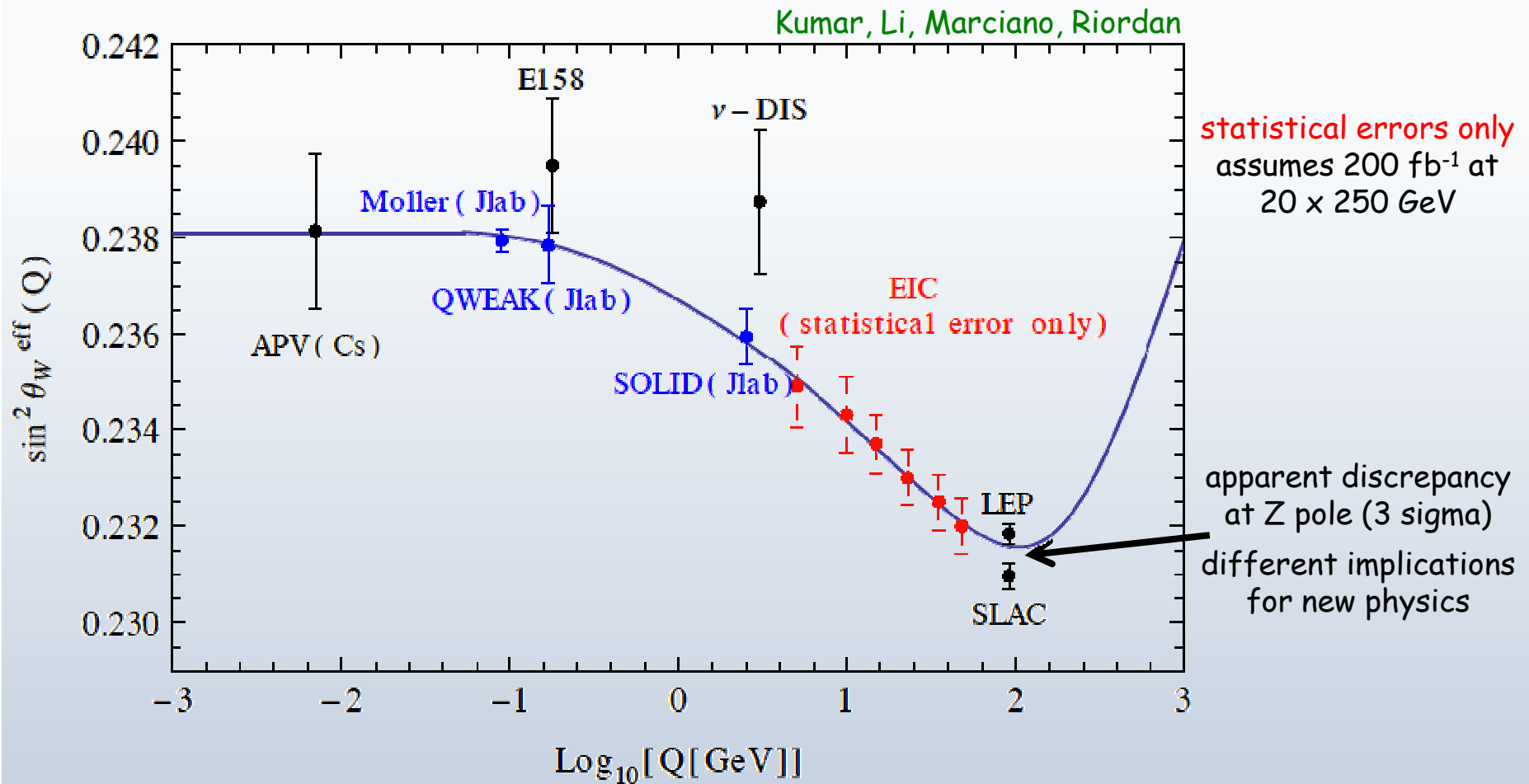
separate up-type and down-type PDF combinations by varying  $y$

$$A^{W^-} = \frac{(\Delta u + \Delta c) - (1-y)^2(\Delta \bar{d} + \Delta \bar{s})}{(u + c) + (1-y)^2(\bar{d} + \bar{s})} \quad A^{W^-} = \frac{(1-y)^2(\Delta d + \Delta s) - (\Delta \bar{u} + \Delta \bar{c})}{(1-y)^2(d + s) + (\bar{u} + \bar{c})}$$

Cabibbo suppressed contributions neglected

## aside: electroweak precision physics at eRHIC ?

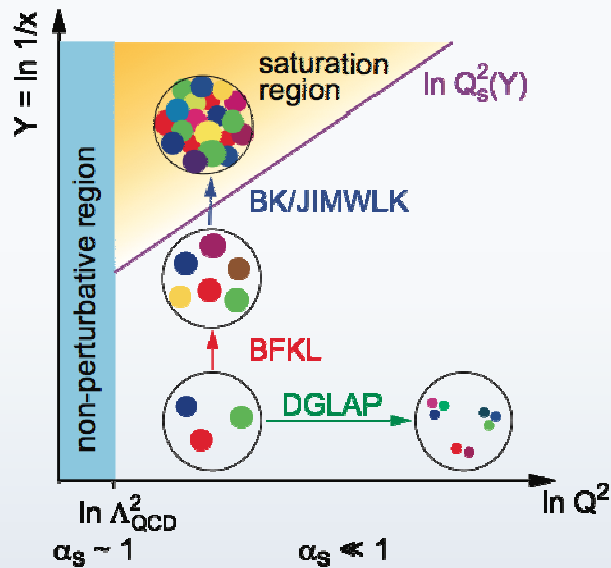
- goal: measure running of  $\sin^2 \Theta_W$  over a wide range of scales  $Q$



- other avenues pursued: electron-tau conversion

Deshpande, Faroughy, Gonderinger, Kumar, Taneja

# saturation in eA DIS - what to expect

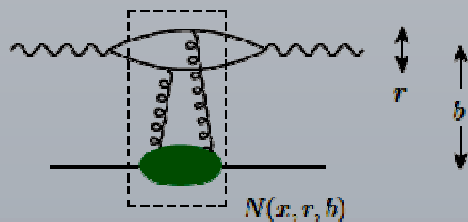


**gluons in nucleus:** terra incognita

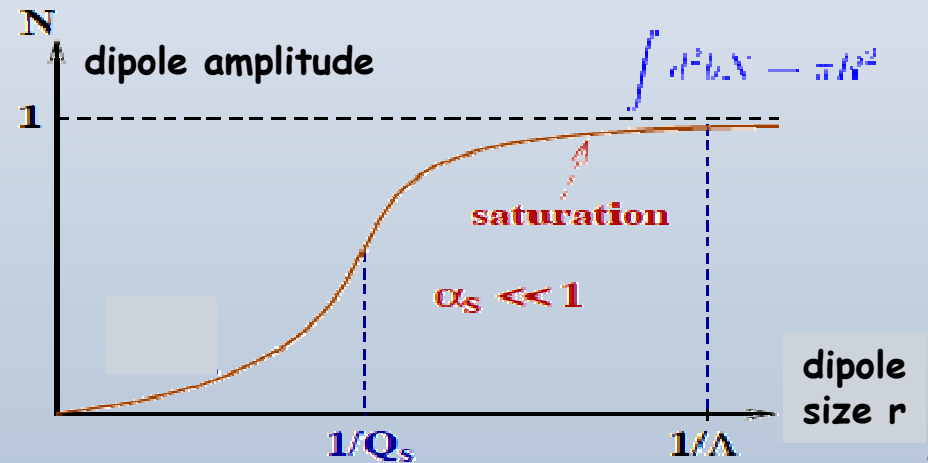
- at high energy/small  $x$ : transition to non-linear regime of strong gluon fields; DGLAP fails
- physics in **saturation regime** controlled by dynamical semi-hard scale  $Q_s(x, A)$
- 1<sup>st</sup> hints for saturation at  $x \approx 10^{-3}$  from RHIC forward hadrons in dAu

estimate relevance of non-linear effects from average strength of dipole scattering in DIS

**recall:** DIS in the proton rest frame: photon splits into a quark-antiquark pair ("color dipole") which scatters off the target proton (= "slow" gluon field)



$$\sigma_{T,L}^{\gamma^* p}(x, Q^2) = \int d^2r db |\Psi_{T,L}(z, \mathbf{r}, Q^2)|^2 d^2b N(x, \mathbf{r}, b)$$



# saturation in eA DIS - cont'd

quantitative estimates

M. Diehl, T. Lappi



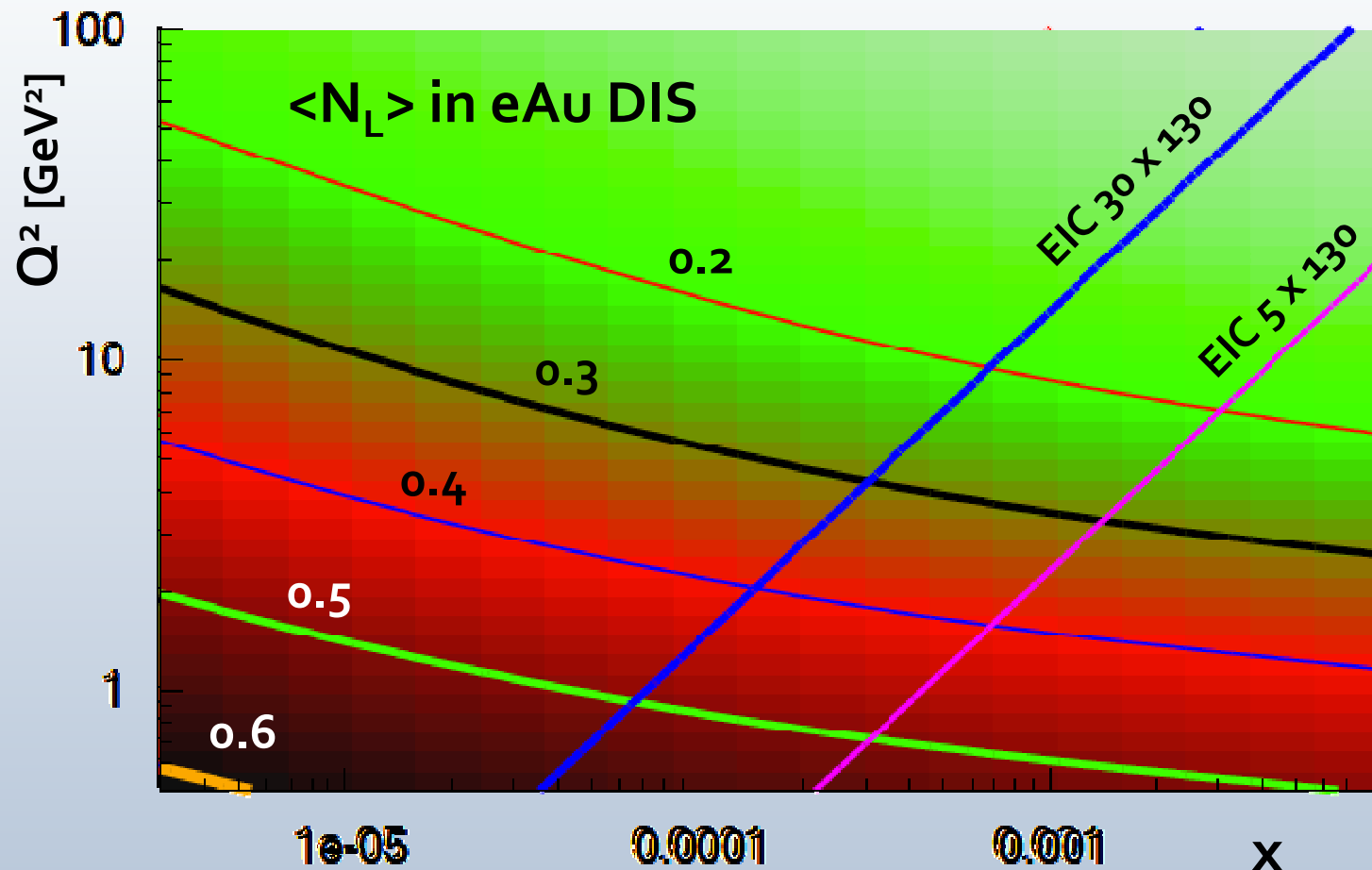
find:  $\sigma_L^2(x, Q^2) \propto F_L(x, Q^2)$  most sensitive to gluons



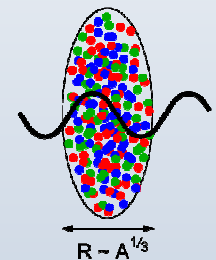
as expected (HERA data): no change in ep



eA much more favorable to study saturation than ep



saturation effects  
in eA benefit from  
nuclear oompf

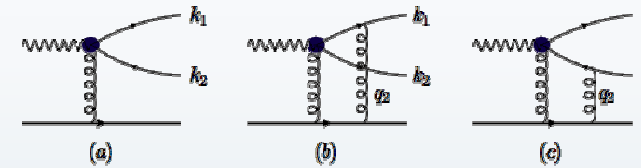
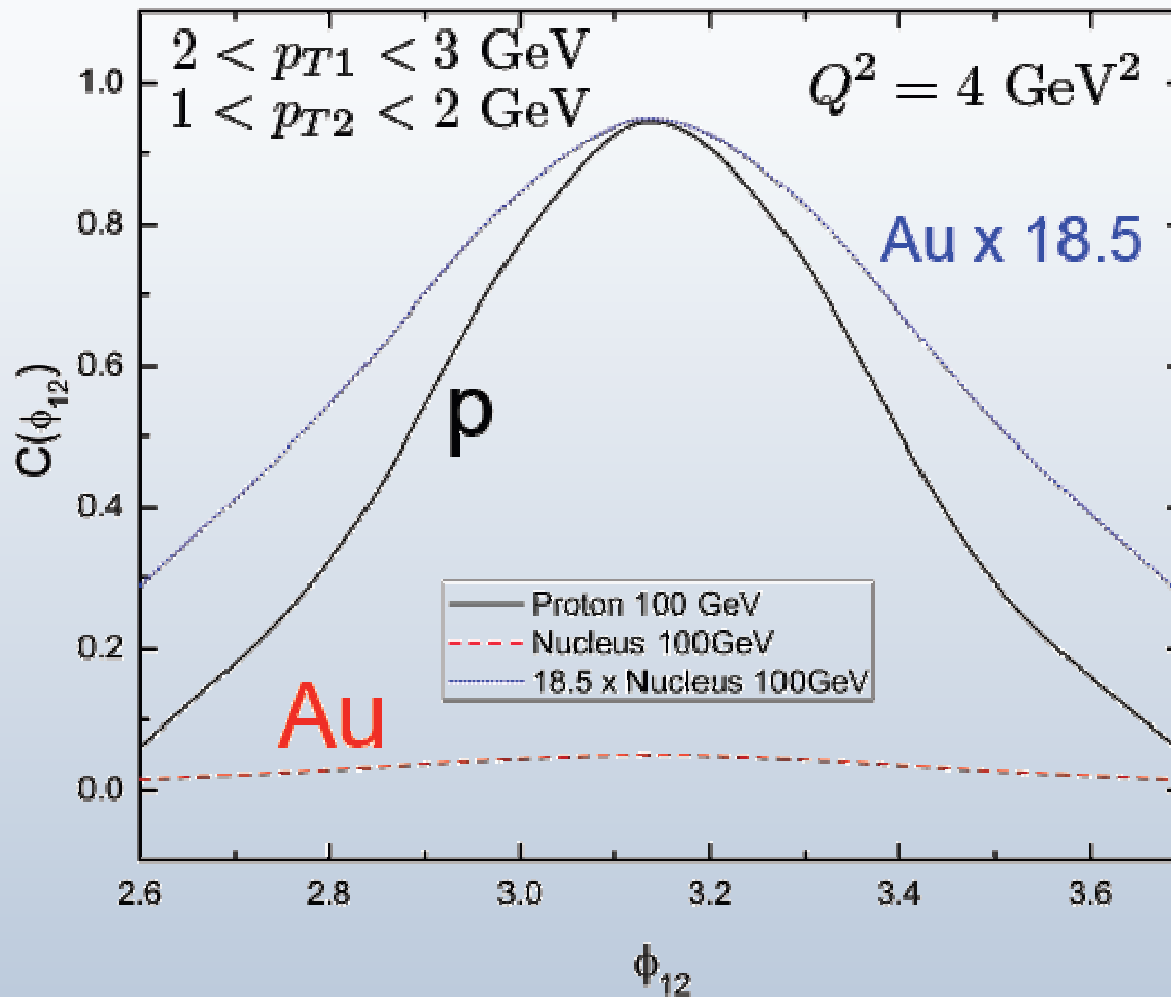


$$Q_{s,A}^2 = A^{1/3} Q_{s,p}^2$$

# di-hadron correlations in eA

never been measured before; **excellent signature for saturation in eA**

Dominguez, Xiao, Yuan



systematic depletion of  
away-side peak with  
increasing nuclear size/energy

can be also obtained in  
TMD factorization  
↔ unintegrated gluon at small  $x$

# hadronization in eA

**physics objectives:** understand quantitatively medium effects such as parton energy loss,  $p_T$  broadening, hadron absorption, ...

**typical observable:** **multiplicity ratios** for ep vs. eA  $R_A^h = \frac{N_A^h(Q^2, \nu, z, p_T^2)/N_A^{DIS}(Q^2, \nu)}{N_p^h(Q^2, \nu, z, p_T^2)/N_p^{DIS}(Q^2, \nu)}$

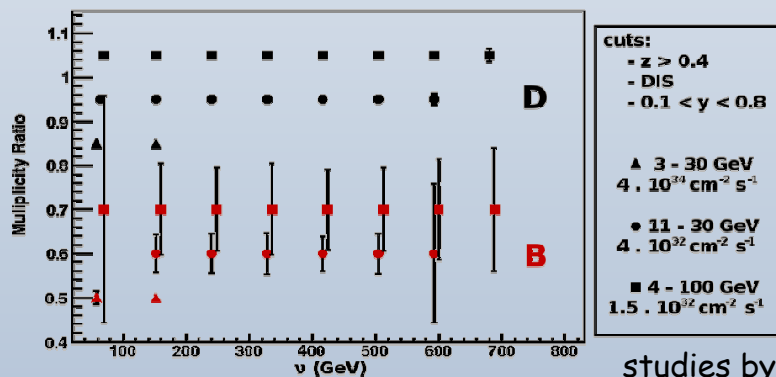
advantage: dependence on nuclear PDFs largely drops out recent NLO study  
Sassot, MS, Zurita

• **hadron attenuation** studies by R. Dupre, A. Accardi

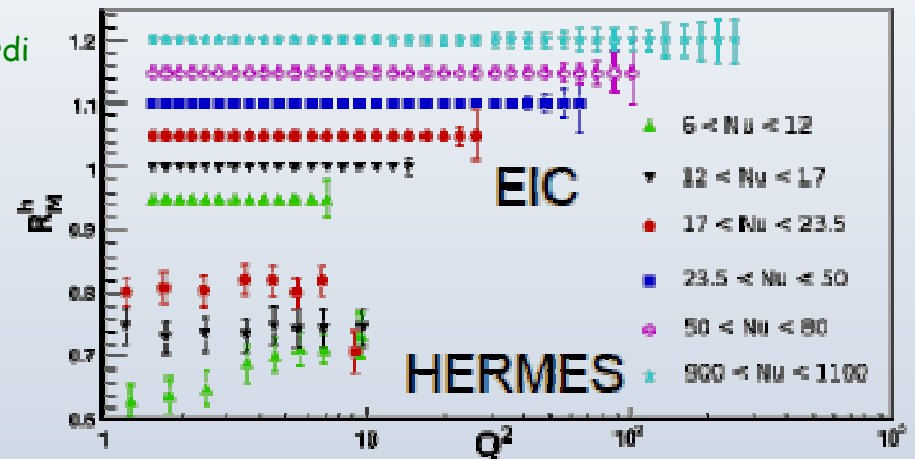
vastly extended reach in  $\nu = q \cdot P/M$

can “dial”  $\nu$  to control characteristic path length in medium

allows for detailed studies of energy loss, ...



studies by R. Dupre, A. Accardi

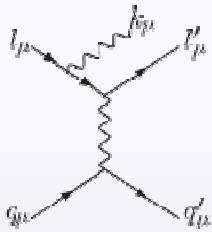


• **heavy quark propagation & energy loss**  
never studied in eA  
quark mass dependence of energy loss

# complication: QED radiative corrections

precision measurements in ep/eA require good understanding of QED corrections

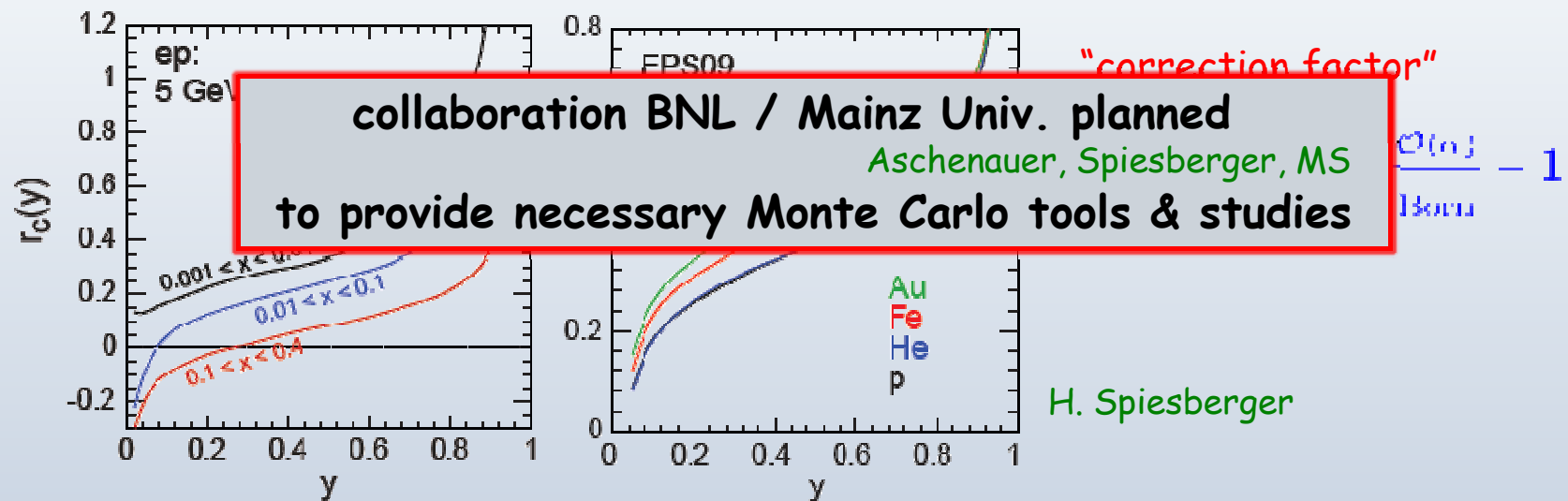
**problem:**



photon radiation strongly affects exp. determination of kinematics

e.g.  $Q^2 = -(1-l')^2 \rightarrow \bar{Q}^2 = -(1-l'-k)^2$

effects are large but we can benefit from HERA experience



extraction of "true" structure functions requires unfolding procedure:

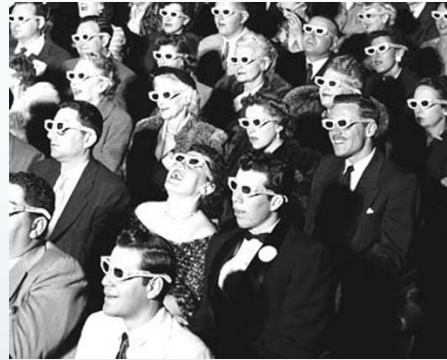
$$F_1^{\text{obs}}(\mathbf{x}, Q^2) = \int d\bar{x} d\bar{Q}^2 R_1(\mathbf{x}, Q^2; \bar{\mathbf{x}}, \bar{Q}^2) F_1^{\text{true}}(\bar{\mathbf{x}}, \bar{Q}^2)$$

"radiator function"  
calculable

# "3D imaging" of nucleons and nuclei

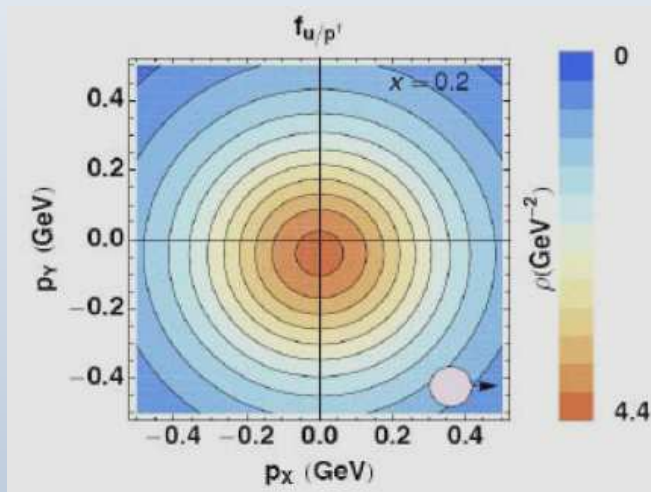
**goal:** going beyond longitudinal momentum structure & collinear factorization

TMDs



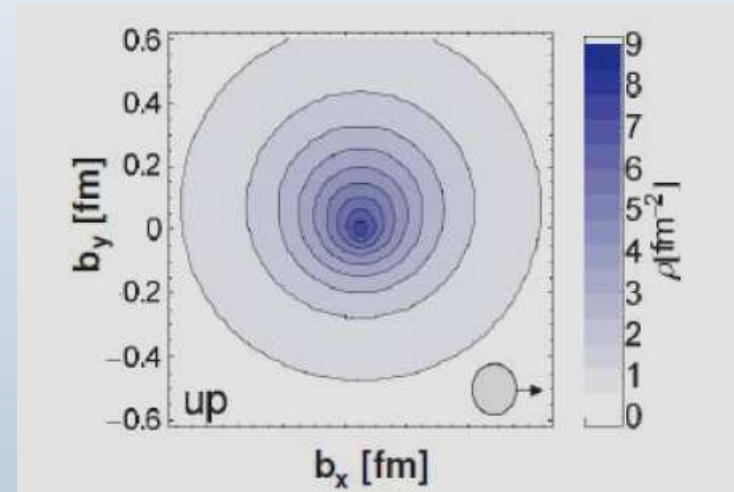
GPDs

2+1 D picture in **momentum space**



Bacchetta, Conti, Radici

2+1 D picture in **impact-parameter space**



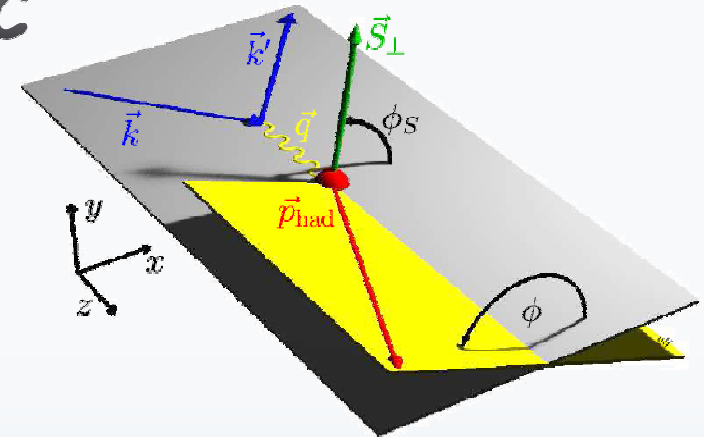
QCDSF collaboration



# TMDs @ eRHIC

suite of observables accessible in  
**azimuthal ( $\phi$ ) asymmetries** in SIDIS

related to entire zoo of TMD functions  
measured at large  $x$  by HERMES & COMPASS



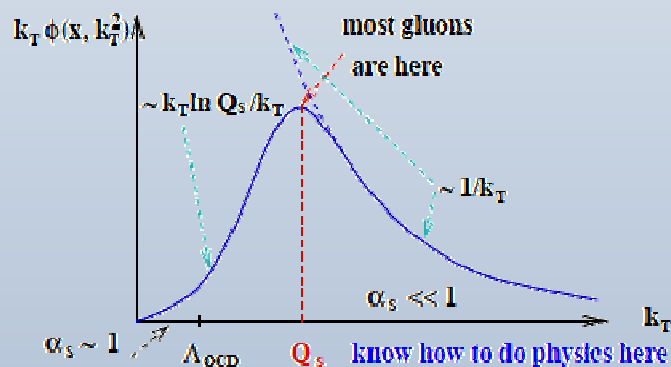
focus on unpolarized  $f_1$  and Sivers function to illustrate underlying physics:

$$f_{q/P}(x, \mathbf{k}_\perp, S) = f_1(x, \mathbf{k}_\perp^2) - \frac{\mathbf{S} \cdot (\hat{\mathbf{P}} \times \mathbf{k}_\perp)}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$

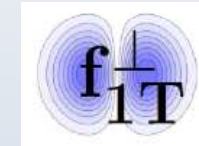
**"unintegrated PDFs"**



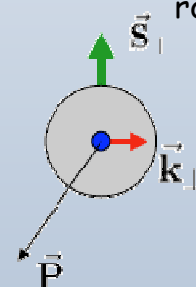
$k_T$  dep. gluon plays prominent role at small  $x$   
rather direct access to saturation scale  $Q_s(x)$   
(e.g. through di-jet correlations in eA)



**"Sivers effect"**



access to 3D imaging in momentum space  
non-trivial role of Wilson lines  
role of spin-orbit correlations & OAM



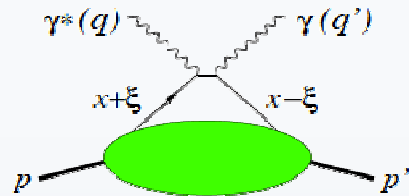
correlation of transverse  
spin of proton with  $k_T$  of  
unpolarized quark

recent work by Z. Kang, J. Qiu

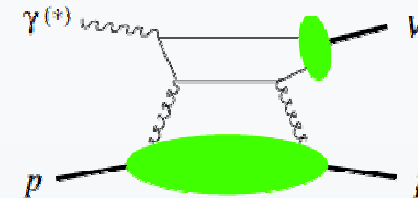
# GPDs: access to transverse position



need to measure & study **exclusive processes**:

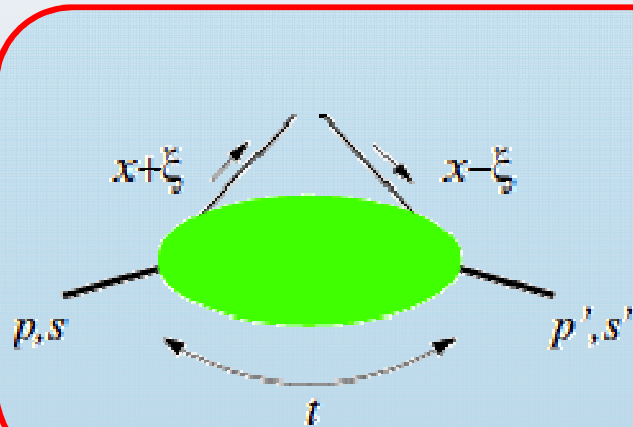


- deeply virtual Compton scattering (DVCS)



- exclusive meson production

- **generalized parton densities** (4 per flavor) needed to describe such processes:



**GPDs depend on  $x$ ,  $\xi$ ,  $t$ ,  $Q^2$**

convenient: symmetric choice of mom. fractions

- $x, \xi$ : mom. fractions w.r.t.  $P = \frac{1}{2}(p + p')$

where  $\xi = (p - p')^+ / (p + p')^+$

in DVCS:  $x$  integrated and  $\xi = x_B / (2 - x_B)$

- $t$ : trade for trans. momentum transfer  $\Delta$

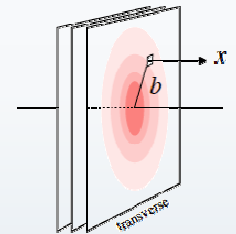
- GPDs represent interference between amplitudes for different nucleon states
- connection to energy-momentum tensor & OAM  $J_i$
- equivalent to dipole model in "double limit" (small  $x$ , large  $Q^2$ )

# transverse imaging @ eRHIC

- obtain GPDs from global analysis of DVCS & exclusive vector meson production  
framework already in place (used to analyze HERA & fixed target data) Muller, Kumericki, Passek-Kumericki

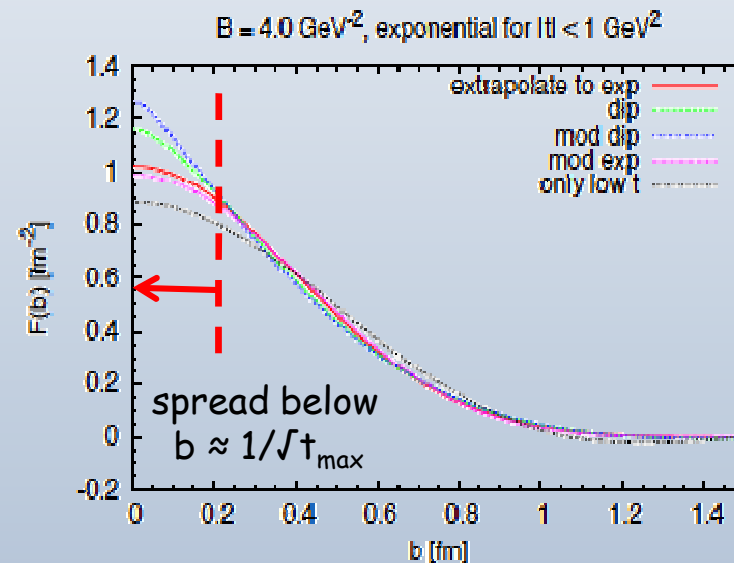
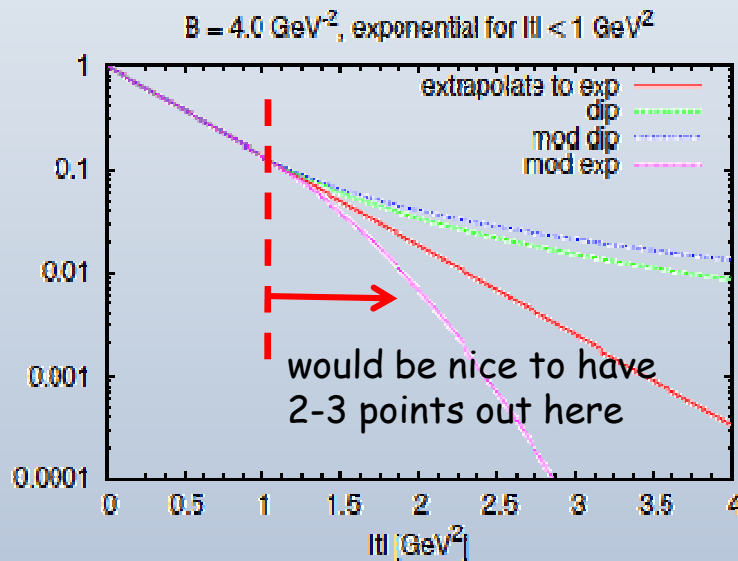
- perform Fourier transformation of GPDs to obtain b-space image

e.g.  $q(x, b^2) \sim \int d^2 \Delta e^{i b \Delta} H^q(x, \xi = 0, t = -\Delta^2)$  where  $\Delta = p' - p$



center

- give
- **challenge:** exclusive processes experimentally very challenging
  - need to integrate Roman pots into IR design
  - † acceptance vs magnet aperture & beam size
  - close collaboration between eRHIC TF & C-AD
- extrapolation





## CONCLUSIONS



eRHIC is the Über-Microscope for precision QCD studies

paradigm shift

from testing QCD to a detailed understanding of QCD  
and the structure of hadrons